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Over 78 000 RR Lyrae Stars in the Galactic Bulge and Disk from the OGLE Survey*

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ABSTRACT

We present an upgrade of the OGLE Collection of RR Lyrae stars in the Galactic bulge and disk. The size of our sample has been doubled and reached 78 350 RR Lyr variables, of which 56 508 are fundamental-mode pulsators (RRab stars), 21 321 pulsate solely in the first-overtone (RRc stars), 458 are classical double-mode pulsators (RRd stars), and 63 are anomalous RRd variables (including five triple-mode pulsators). For all the newly identified RR Lyr stars, we publish time-series photometry obtained during the OGLE Galaxy Variability Survey.

We present the spatial distribution of RR Lyr stars on the sky, provide a list of globular clusters hosting RR Lyr variables, and discuss the Petersen diagram for multimode pulsators. We find new RRd stars belonging to a compact group in the Petersen diagram (with period ratios $P_{1O}/P_{F} \approx 0.74$ and fundamental-mode periods $P_{F} \approx 0.44$ d) and we show that their spatial distribution is roughly spherically symmetrical around the Milky Way center.

Key words: *Stars: variables: RR Lyrae – Stars: oscillations – Galaxy: bulge – Galaxy: disk – Catalogs*

*Based on observations obtained with the 1.3-m Warsaw telescope at the Las Campanas Observatory of the Carnegie Institution for Science.

1. Introduction

RR Lyrae stars play a crucial role in understanding the formation, composition, and kinematics of the Galactic halo and thick disk. These radially pulsating horizontal-branch stars, with periods ranging from 0.2 to 1 d, belong to the very old stellar population (older than ≈ 10 Gyr). RR Lyr variables constitute the most numerous group of classical pulsating stars, follow a relatively narrow period–luminosity relation and have distinctive light curves, which make them primary distance indicators among old, low-mass stars.

In recent years, various wide-field sky surveys – LINEAR (Sesar *et al.* 2013), Catalina Sky Survey (Drake *et al.* 2014), Pan-STARRS (Hernitschek *et al.* 2016, Sesar *et al.* 2017), SuperWASP (Greer *et al.* 2017), ASAS-SN (Jayasinghe *et al.* 2018, 2019, 2020), Gaia (Holl *et al.* 2018, Clementini *et al.* 2019) – have published extensive catalogs of RR Lyr stars in the Milky Way. These samples have been used to investigate the structural properties of the Galactic halo, including the exploration of stellar streams composed of material that has been tidally striped from dwarf galaxies (*e.g.,* Torrealba *et al.* 2015, 2019, Hernitschek *et al.* 2018, Koposov *et al.* 2019). However, due to crowding and blending, the Galactic bulge and disk region was either intentionally avoided by the variability surveys or the published catalogs of variable stars were affected by significantly reduced levels of completeness and purity.

The Optical Gravitational Lensing Experiment (OGLE) is a photometric sky survey devoted to long-term monitoring of densely populated regions, such as the Galactic bulge and disk. So far, OGLE published a catalog of more than 39 000 RR Lyr stars identified over 182 square degrees toward the central parts of the Milky Way (Soszyński *et al.* 2011, 2014, 2017). Additionally, 45 RR Lyr stars were found by Pietrukowicz *et al.* (2013) in the OGLE pilot survey of the Galactic disk. The OGLE Collection of Variable Stars (OCVS) has enabled us to gain deep insight into the structure of the Milky Way bulge (Pietrukowicz *et al.* 2015), but also to explore the structure of the Sagittarius Dwarf Galaxy (SgrDG, Hamanowicz *et al.* 2016, Ferguson and Strigari 2019). Accurate and well-sampled OGLE light curves have been used to investigate a variety of phenomena occurring in RR Lyr stars: additional radial and non-radial modes, the Blazhko effect, switching of the pulsation modes, binarity, Oosterhoff dichotomy (*e.g.,* Netzel *et al.* 2015, 2018, Smolec *et al.* 2016, Prudil *et al.* 2017, 2019ab, Das *et al.* 2018, Netzel and Smolec 2019). Moreover, the highly complete OGLE samples of variable stars have been commonly used for the validation of the catalogs obtained from other projects (*e.g.,* Braga *et al.* 2019, Clementini *et al.* 2019, Plachy *et al.* 2019).

In 2013, the OGLE team launched a new observational subproject named the Galaxy Variability Survey (GVS), with the main goal to photometrically monitor stars in the Galactic disk and outer bulge. The GVS is shallower than the regular OGLE survey (exposure time of 25 s *vs.* 100–150 s in the regular OGLE project), but it covers a much larger area of the sky – about 3000 square degrees in total.

The multi-epoch photometric data collected by the GVS project have so far been used by Udalski *et al.* (2018) to discover over a thousand new classical, type II, and anomalous Cepheids in the Milky Way. The extended catalog of Cepheids was used by Mróz *et al.* (2019) to derive an accurate rotation curve of our Galaxy and by Skowron *et al.* (2019) to construct a three-dimensional map of the Galactic disk and to study the recent star formation history in the Milky Way.

In this paper, we present the collection of RR Lyr stars identified among over a billion stars regularly observed by the GVS project in the Galactic bulge and disk. Our new sample doubles the number of Galactic RR Lyr stars included so far in the OCVS. The completeness and purity of our collection is very high, which makes it complementary to other large RR Lyr catalogs produced by wide-field surveys.

The paper is organized as follows. An overview of the OGLE photometric data is given in Section 2. In the following section, we briefly review the selection and classification criteria of the RR Lyr stars. The structure of the collection of RR Lyr stars is described in Section 4. Section 5 presents the analysis of the completeness of the resulting sample and its comparison with other large-scale catalogs of RR Lyr stars. Globular cluster members and multi-mode RR Lyr variables are discussed in the following two sections. Finally, Section 8 summarizes our results.

2. Observations and Data Reduction

The OGLE project is a large-scale, long-term, two-band (*I*- and *V*-band) photometric survey aimed at systematic exploration of the variable sky. Since 2010 (when the fourth phase of the OGLE survey, OGLE-IV, started), the project has used 32-chip mosaic CCD camera, with a field of view of 1.4 square degrees and a pixel scale of $0\overset{\prime\prime}{.}26$, mounted on the 1.3-m Warsaw Telescope at Las Campanas Observatory in Chile (the Observatory is operated by the Carnegie Institution for Science).

The OGLE GVS subsurvey has been carried out since 2013. Together with the regular OGLE-IV survey, the GVS project monitors brightness of about two billion stars located in the area of more than 3000 square degrees along the Galactic plane. The GVS footprint spans about 230 degrees in the Galactic longitude and reaches 7 degrees above and below the Galactic plane in the disk region and ± 15 degrees in the bulge region. At the end of 2019, images covering 2750 square degrees in the Galactic disk and bulge (including the regular OGLE fields) have already been reduced and this work presents the collection of RR Lyr stars detected in this region. The remaining GVS fields will be reduced soon, and variable stars identified in this region will be added to the OCVS.

The majority of the GVS observations were obtained through the Cousins *I*-band filter with the exposure time of 25 s. The *V*-band light curves, currently unavailable for most of the stars, will be added to the collection in the future. The time series collected by GVS project are not as well sampled as those from the regular OGLE observations. The total number of points per light curve ranges from about 20 to 200, with a median value of 112 epochs. The timespan ranges from several months to several years, with a typical value of 3 yr.

The GVS project is about 1 mag shallower than the regular OGLE survey, so the saturation limit of the GVS photometry is at about 11 mag, while the faintest stars for which useful information about their variability can be obtained have $I \approx 19.5$ mag. For further details on the GVS project, data reduction, and astrometric calibrations we refer the reader to the papers by Udalski *et al.* (2015, 2018).

3. Selection and Classification of RR Lyr Stars

Our search for RR Lyr stars in the GVS fields was carried out in two stages. An initial stage of the selection was described by Udalski *et al.* (2018). Briefly, stars that left significant residua on the difference images produced by the OGLE reduction pipeline were selected. A visual inspection of their light curves in conjunction with the Fourier analysis and positions in the color–magnitude diagram allowed us to detect more than one thousand previously unknown Cepheids and several thousand RR Lyr stars (Udalski 2017).

We began the second stage of our variable stars' selection from the massive period search for all GVS *I*-band light curves with at least 15 data points. For this purpose, we applied the FNPEAKS code[†] which uses the Discrete Fourier Transform algorithm. The FNPEAKS code provides the most significant periods with amplitudes and signal-to-noise ratios. We have performed a period analysis for more than a billion light curves.

Then, objects with periods shorter than 50 d and the largest signal-to-noise ratio of their periodicities were initially classified by using light-curve template fitting. We followed the analysis undertaken by Soszyński *et al.* (2019) for variable stars in the Magellanic Clouds. The algorithm is based on the carefully selected light curves of pulsating stars and eclipsing binary systems previously detected by the OGLE team in the Galactic bulge and Magellanic Clouds. We chose the best sampled single-periodic light curves representing a wide range of variability types. Each light curve was folded with the pulsation or orbital period and binned into 1000 bins, while its amplitude was rescaled to 1 mag. Example template light curves were showed in the papers by Soszyński *et al.* (2016a, 2019).

For each star analyzed by the template fitting program, we obtained the most probable variability type with a parameter reflecting the goodness of the fit. Then, the best candidates for pulsating stars were revised during the visual inspection of their light curves. Besides RR Lyr stars, we detected, among others, new Cepheids, δ Sct stars, long-period variables, eclipsing binaries, and various types of rotating variables. Our classification was based largely on the light-curve characteristics, including the parameters of the *I*-band light curve Fourier decomposition. Candidates

[†]http://helas.astro.uni.wroc.pl/deliverables.php?lang=en&active=fnpeaks

for double-mode RR Lyr stars were preselected on the basis on their period ratios and their light curves were also subject to visual inspection. The final phase of our selection procedure was a match of the OGLE database with other large catalogs of RR Lyr stars in the Milky Way (Section 5), which additionally brought approximately 600 RR Lyr variables overlooked in the previous stages of our variability search.

As a result, we identified 39 232 *bona fide* RR Lyr stars. We divided this sample into four classes: fundamental-mode RRab stars, first-overtone RRc stars, double-mode RRd stars, and anomalous multi-mode (double- and triple-mode) RRd stars. This classification was based on the pulsation periods, light curve morphology, and period ratios (in the case of multi-mode pulsators).

Some RRc stars can have almost symmetric light curves with morphologies similar to those of close binary systems phased with half their orbital period. To minimize the contamination from close binary systems, we required perceptible skewness of a light curve to classify a star as an RRc variable. This requirement may reduce the completeness of our sample of RRc stars, especially for fainter objects (Section 5).

4. The OGLE Collection of Galactic RR Lyr Stars

RR Lyr variables identified in the GVS fields have been added to the OCVS. Now, the OGLE sample contains in total 78 350 Galactic RR Lyr stars: 56 508 RRab, 21 321 RRc, and 521 RRd stars (including 63 anomalous RRd stars). The complete list of the OGLE Galactic RR Lyr stars along with their *I*-band and *V*-band light curves (if available) are provided online through a user-friendly WWW interface or FTP sites:

http://ogle.astrouw.edu.pl
ftp://ftp.astrouw.edu.pl/ogle/ogle4/OCVS/blg/rrlyr/
ftp://ftp.astrouw.edu.pl/ogle/ogle4/OCVS/gd/rrlyr/

The newly identified variables have extended the lists of previously published RR Lyr stars in the Galactic bulge (Soszyński *et al.* 2014, 2017) and Galactic disk (Pietrukowicz *et al.* 2013). We have kept the naming convention used in the OCVS: OGLE-BLG-RRLYR-NNNNN and OGLE-GD-RRLYR-NNNNN (for bulge and disk RR Lyr stars, respectively), where NNNNN is a five-digit consecutive number. For all stars, we provide their basic properties: pulsation modes, J2000 equatorial coordinates, periods, intensity mean magnitudes, amplitudes, and parameters of light curve Fourier decomposition. The pulsation periods were improved with the TATRY code by Schwarzenberg-Czerny (1996). For each star we provide a $60'' \times 60''$ finding chart.

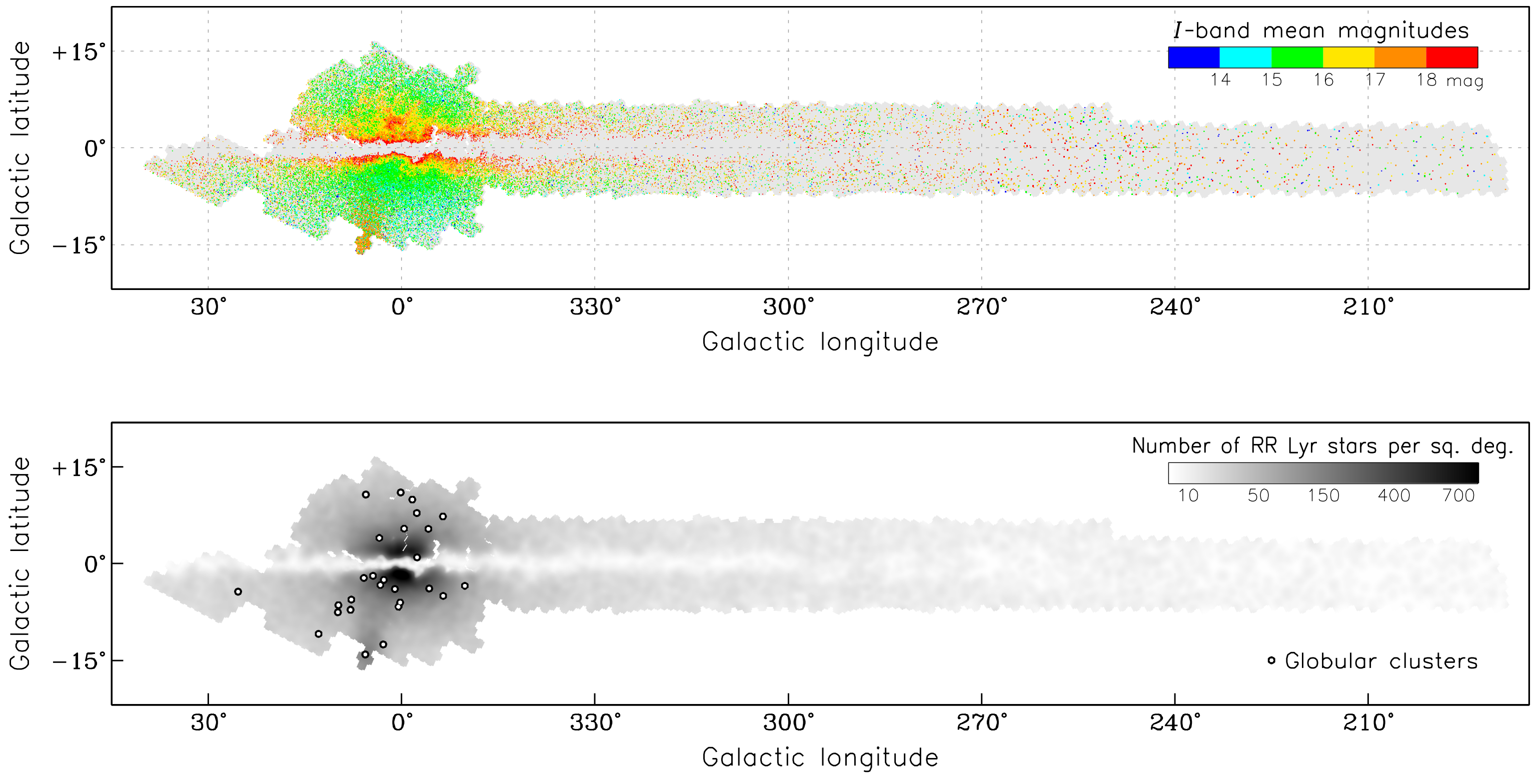

Fig. 1. Distribution of Galactic RR Lyr stars in Galactic coordinates. In the *upper panel* the colors of the points indicate magnitudes of each star, following the color code in the panel. The gray area shows the OGLE-IV footprint. Lower panel presents a surface density map of RR Lyr stars. We used the square-root scaling to show the full dynamic range of the map. White circles indicate the positions of 27 globular clusters hosting RR Lyr stars.

We also upgraded light curves and parameters of 762 Galactic RR Lyr stars already included in the OCVS, but not observed so far during the regular OGLE-IV project. Most of these variables were discovered from the OGLE-III observations (Soszyński *et al.* 2011, Pietrukowicz *et al.* 2013). The OGLE collection of RR Lyr stars will continue to grow as we discover new variables in the newly reduced fields monitored by the GVS survey.

4.1. Spatial Distribution

Fig. 1 presents the distribution of RR Lyr variables on the sky. In the upper panel, different colors of the points represent different *I*-band mean magnitudes of the stars. As one can see, in the Galactic bulge and in the adjacent section of the disk, RR Lyr stars become gradually fainter in the lines-of-sight closer to the Galactic plane. This is a result of heavy interstellar extinction in this area. For this reason, most of RR Lyr stars located in the regions closest to the Galactic equator are not accessible to the OGLE survey. These highly obscured areas have been explored in the near-infrared domain by the VISTA Variables in Vía Láctea (VVV) survey (Gran *et al.* 2016, Minniti *et al.* 2017, Contreras Ramos *et al.* 2018, Majaess *et al.* 2018).

In the lower panel of Fig. 1, we present a surface density map of our RR Lyr sample. We used a square root scaling to show the full dynamic range this map. The surface density ranges from less than one RR Lyr star per square degree in the regions close to the Galactic anticenter to about 1000 RR Lyr variables in the most populated fields in the bulge. In the lower panel of Fig. 1, we also present positions of 27 globular clusters hosting RR Lyr stars (Section 6).

4.2. Magnitude Distribution

Our collection contains a significant number of RR Lyr stars belonging to the SgrDG. They are well visible in Fig. 2, where the distributions of the apparent mean *I*-band magnitudes of the Galactic RR Lyr stars are shown. The three histograms display: magnitude distribution of the RR Lyr stars found by Soszyński *et al.* (2011, 2014, 2017) in the regular OGLE fields toward the Galactic bulge ("old" variables), RR Lyr variables detected in the outer bulge observed by the GVS ("new"), and RR Lyr stars identified in the Galactic disk fields. The SgrDG members produce a peak around a magnitude of 17.6 mag in the first two of these distributions.

The "new" variables in the central regions of the Milky Way are on average brighter than the "old" ones, which is a result of a much smaller interstellar extinction in the outer bulge than in the inner bulge, monitored by the regular OGLE survey. Different depths of the GVS and regular OGLE project can be seen at the edges of the distributions – the faintest RR Lyr stars detected from the regular survey have mean *I*-band luminosities of about 20.5 mag – approximately one magnitude fainter than the GVS detection limit. On the other hand, the saturation limit is respectively brighter in the GVS dataset.

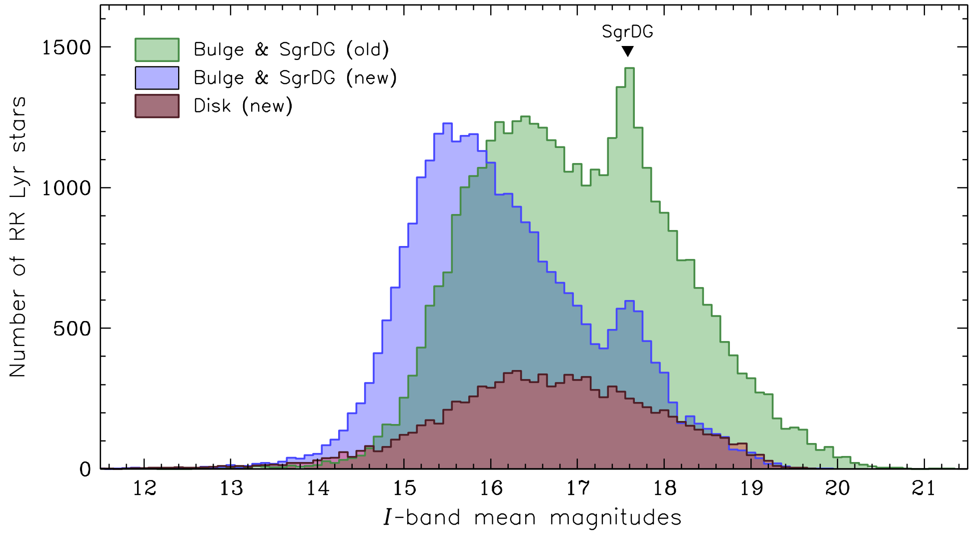

Fig. 2. Distributions of the mean *I*-band magnitudes of RR Lyr stars in the Galactic bulge and disk. Different colors of the histograms show three samples: green – RR Lyr stars found by Soszyński *et al.* (2011, 2014, 2017) toward the Galactic bulge in the regular OGLE fields, violet – objects detected toward the bulge in the in the GVS fields, brown – RR Lyr variables identified in the GVS fields in the Galactic disk.

5. Completeness and Cross-Check with Other Catalogs

The completeness and purity levels of our collection of RR Lyr stars are affected by various factors. First of all, we draw the reader's attention to the fact that the OGLE-IV mosaic camera has technical gaps between CCD chips, which decrease the absolute completeness of our sample by 6–7%. Objects that fell into these "dead zones" of our detector have not been observed at all by the OGLE survey.

Considering only those objects that have been observed by OGLE, the completeness of our collection is a strong function of the temporal sampling, brightness, amplitudes, presence of the Blazhko effect, and, most of all, the pulsation modes of RR Lyr stars. The completeness and purity levels of our collection are definitely largest for RRab stars, since they have characteristic light curves that are not easily mistaken for other types of periodic variables. We also expect that the efficiency of our search for RRd variables is larger than for RRc stars, because two periods with a certain ratio unambiguously identify an object as a double-mode pulsator.

In order to assess the completeness of our sample, we used stars located in the overlapping parts of adjacent GVS fields. Such objects have double entries in the OGLE database, so we had the opportunity to detect them twice during our selection process (however, the final version of our collection contains only one entry per star – usually the one with larger number of data points). Because stars located near the edges of the fields are often affected by a smaller number of epochs, we took into consideration only those light curves that consisted of more than 30 data points. We *a posteriori* checked that 1735 RR Lyr stars in our collection have their duplicates in other GVS fields, so we had a chance to find 3470 counterparts. We independently detected 3289 of them, which gives the completeness level of more than 94% for the whole sample. For RRab variables only, the completeness is about 96%, while for RRc stars it is equal to 91%.

Using the same method, we estimated the efficiency of our RR Lyr search in various luminosity ranges. The completeness level for RRc variables drops below 80% for objects fainter than $I = 17$ mag and below 30% for stars fainter than $I = 18$ mag. For RRab stars, the completeness level is still above 80% for objects with the mean luminosity around 18 mag.

To improve the completeness of the RR Lyr collection, we cross-matched our initially identified sample with a number of extensive catalogs containing Galactic RR Lyr variables: the International Variable Star Index (VSX, Watson *et al.* 2006), ASAS (*e.g.*, Pojmański 2002), ASAS-SN (Jayasinghe *et al.* 2018, 2019, 2020), SuperWASP (Greer *et al.* 2017), Catalina Sky Survey (Drake *et al.* 2014), ATLAS (Heinze *et al.* 2018), VVV (Gran *et al.* 2016, Minniti *et al.* 2017, Contreras Ramos *et al.* 2018, Majaess *et al.* 2018), Pan-STARRS (Hernitschek *et al.* 2016, Sesar *et al.* 2017), and Gaia Data Release 2 (Holl *et al.* 2018, Clementini *et al.* 2019). For some of these surveys (ASAS, Catalina Sky Survey, SuperWASP), we found only several common RR Lyr stars, due to small overlaps between sky footprints or observed magnitude ranges. By combining our sample with other lists of RR Lyr stars (VSX, ASAS-SN, ATLAS, VVV, Pan-STARRS), we found from about 2000 to 9000 matches, and the largest overlap – over 15 000 RR Lyr stars – was found with the Gaia DR2 catalog. In total, 23 604 of RR Lyr stars from our collection ($\approx 60\%$) have been found in at least one of the explored catalogs, so approximately 40% of our sample are likely new detections.

We also carefully studied objects overlooked during our selection and classification process (Section 3), but classified as RR Lyr variables in the above catalogs. We found nearly 40 000 such objects in the OGLE GVS database (most of them from the Pan-STARRS catalog, but also over 5000 RR Lyr candidates from the Gaia DR2 sample) and we visually inspected their OGLE light curves. This exercise yielded extra 604 RR Lyr stars, which were added to the final version of our collection increasing its completeness. The majority of these variables were missing from the preliminary version of the OCVS due to their poorly-sampled or noisy light curves. We also overlooked some RRc stars that suffer various selection effects. We must also notice that a number of RR Lyr candidates from external catalogs cannot be unambiguously categorized using OGLE light curves, because of sparse photometry. On the other hand, among RR Lyr candidates we also found thousands of stars obviously belonging to other variability types: eclipsing binaries, Cepheids, δ Sct stars, spotted variables, or sometimes constant stars.

6. RR Lyr Stars in Globular Clusters

It has long been known that RR Lyr variables provide firm constraints to study properties of globular clusters and other ancient stellar systems. In the paper describing the OGLE collection of RR Lyr stars in the Galactic bulge (Soszyński *et al.* 2014), we provided a list of 15 globular clusters hosting RR Lyr variables. In this work, we expand this list by adding 12 other globular clusters located in the OGLE GVS fields, including M62 (NGC 6266) – one of the most RR Lyr-rich globular cluster in the Galaxy (Contreras *et al.* 2010). The sky positions of the all globular clusters containing RR Lyr stars are plotted in the lower panel of Fig. 1.

Table 1

Globular clusters containing RR Lyr stars

Cluster name	RA (J2000)	Dec (J2000)	Cluster radius [′]	N_{RR}	$N_{fieldRR}$ (estimated)
M62 (NGC 6266)	$17^h01^m13^s$	$-30°06'44''$	15.0	210	2.8
NGC 6284	$17^h04^m29^s$	$-24°45'53''$	6.2	8	0.6
NGC 6287	$17^h05^m09^s$	$-22°42'29''$	4.8	4	0.3
NGC 6293	$17^h10^m10^s$	$-26°34'54''$	8.2	7	1.9
M9 (NGC 6333)	$17^h19^m12^s$	$-18°30'59''$	12.0	13	1.6
NGC 6380	$17^h34^m28^s$	$-39°04'09''$	3.6	9	0.3
M28 (NGC 6626)	$18^h24^m33^s$	$-24°52'12''$	11.2	21	2.3
NGC 6638	$18^h30^m56^s$	$-25°29'47''$	7.3	22	1.0
NGC 6642	$18^h31^m54^s$	$-23°28'35''$	5.8	23	0.6
M70 (NGC 6681)	$18^h43^m13^s$	$-32°17'31''$	8.0	5	0.4
NGC 6712	$18^h53^m04^s$	$-08°42'22''$	9.8	13	0.6
NGC 6717	$18^h55^m06^s$	$-22°42'03''$	5.4	3	0.1

Table 1 summarizes the basic parameters of the newly added clusters: their coordinates, radii [‡], and numbers of RR Lyr stars detected within one cluster angular radius from the cluster center. In the last column of Table 1, we provide expected numbers of field RR Lyr stars lying by chance in the same line-of-sight as globular clusters. These numbers were estimated by counting RR Lyr variables in the rings around each cluster. In Table 1, we included only those clusters that contain at least three more RR Lyr stars than the expected number of field variables inside an area outlined by the cluster radius. In the FTP sites of the collection, we provide files gc.dat containing 668 RR Lyr stars found in the area occupied by globular clusters. Note that some of these variables may not be physically related to the clusters, but the discrimination between field and cluster RR Lyr stars is beyond the scope of this paper.

[‡]The parameters of the globular clusters have been taken from the web page:
http://messier.obspm.fr/xtra/supp/mw_gc.html

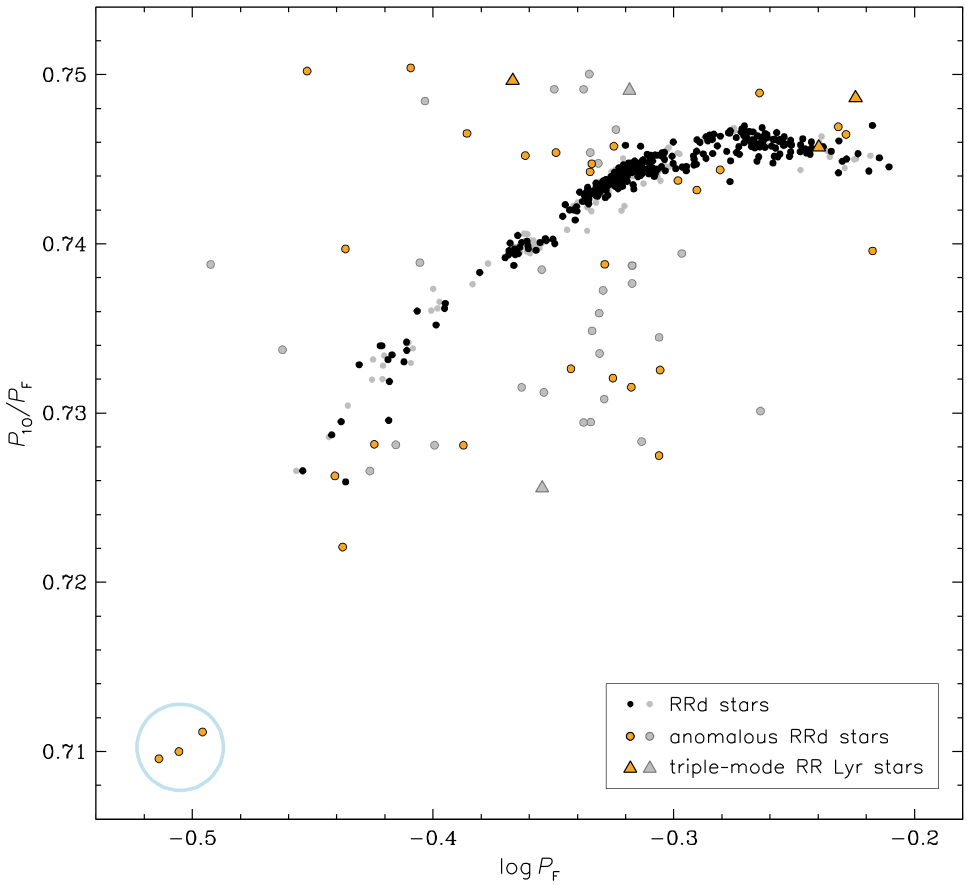

Fig. 3. Petersen diagram for Galactic RRd stars in the OCVS. Black and yellow points indicate objects included in this upgrade of the collection, while gray points mark multimode RR Lyr stars published by Soszyński *et al.* (2011, 2014, 2017). Large light-blue circle marks the position of three short-period double-mode anomalous RRd stars (their light curves are shown in Fig. 4).

7. Multimode RR Lyr Stars

RR Lyr variables oscillating simultaneously in two or three radial modes (RRd stars) are a rich source of information on stellar pulsation and evolution theories. One of the OGLE results in this field was the discovery of a new subclass of multimode RR Lyr variables, named anomalous RRd stars (Soszyński *et al.* 2016b). With this upgrade of the OCVS, the number of known anomalous RRd stars in the Milky Way has increased by a factor of two (from 31 to 63). In turn, the sample of Galactic "classical" RRd stars in the OGLE collection has been tripled: from 148 to 458 objects.

This disproportionate increase in the number of RRd variables in relation to the total sample of RR Lyr stars in our collection, is due to the fact that the incident rate of double-mode RR Lyr stars seems to be a strong function of metallicity. RRd stars constitute only about 0.5% of all RR Lyr variables in the Galactic bulge, but the relative number of RRd stars is gradually increasing with the distance from the Milky Way center and exceeds 3% around Galactic anti-center. For comparison, the incident rates of RRd stars in the Large and Small Magellanic Clouds are about 5% and 10%, respectively.

Fig. 3 shows the Petersen diagram, in which the period ratio, P_{1O}/P_{F}, is plotted against the logarithm of the fundamental-mode period P_{F}. The Petersen diagram is a sensitive probe of masses and chemical content of double-mode RR Lyr stars, because positions of double-mode pulsators in this diagram strongly depend on stellar properties (*e.g.,* Popielski *et al.* 2000). Gray symbols in Fig. 3 indicate multimode RR Lyr stars in the Galactic bulge published by Soszyński *et al.* (2011, 2014, 2017), while black and yellow symbols are new detections. Our classification of the anomalous RRd stars, was largely based on their position in the Petersen diagram, but we also took into account ratios of amplitudes associated to both pulsation modes, light curve morphology, and presence of the Blazhko effect (Soszyński *et al.* 2016b).

We also found three new triple-mode variables (marked with triangles in Fig. 3). Following Soszynski *et al.* (2017), we classified these triple-mode pulsators as anomalous RRd stars. Table 2 gives the complete list of five triple-mode RR Lyr variables included in the OCVS.

Table 2

Triple-Mode RR Lyr stars in the galactic bulge and disk

Identifier	P_{F} [days]	A_{F} [mag]	P_{1O} [days]	A_{1O} [mag]	$P_{2O\|3O}$ [days]	$A_{2O\|3O}$ [mag]
OGLE-BLG-RRLYR-24137	0.4419265	0.154	0.3206446	0.125	0.2199141	0.056
OGLE-BLG-RRLYR-38791	0.4804440	0.194	0.3598870	0.117	0.2865899	0.043
OGLE-BLG-RRLYR-57262	0.5964392	0.199	0.4465113	0.161	0.3558438	0.045
OGLE-GD-RRLYR-05935	0.4296175	0.108	0.3220625	0.090	0.2561699	0.039
OGLE-GD-RRLYR-09200	0.5758730	0.215	0.4294370	0.127	0.3415855	0.058

At the bottom of the Petersen diagram, the blue circle marks three double-mode pulsators with exceptionally low period ratios of around 0.71. We also classified these stars as anomalous RRd variables. Their disentangled light curves are shown in Fig. 4. Note that both periods have relatively large amplitudes in each of the three objects, which indicates that both periods are related to the radial (fundamental-mode and first-overtone) pulsation modes.

It is worth noting that Fig. 3 does not show all double-periodic variables in our collection. At least six variables have secondary periods shorter by a factor of 0.68–0.71 than the primary period. In most such cases the amplitudes of the addi-

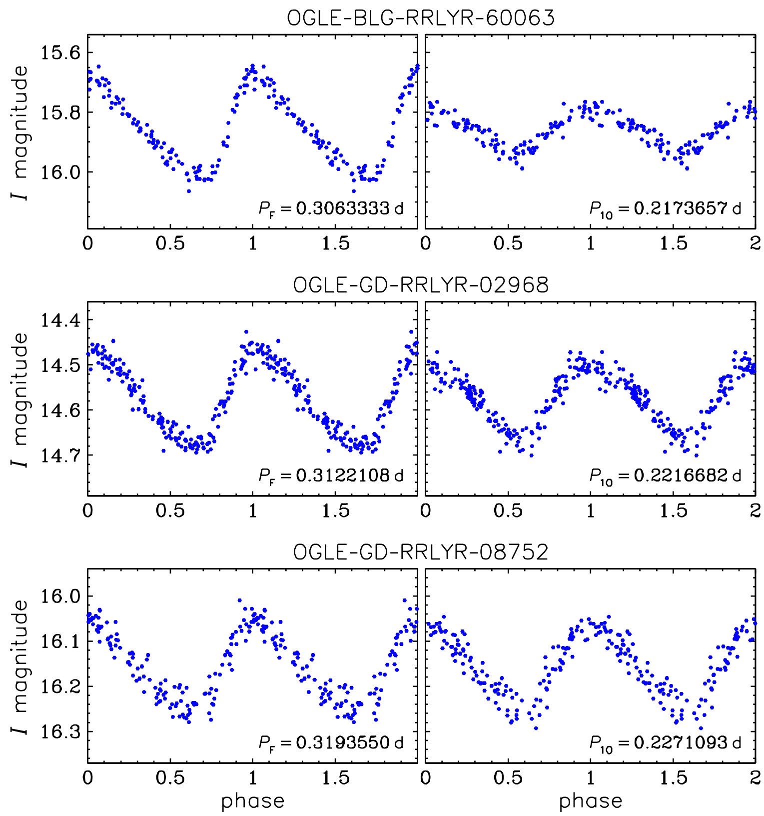

Fig. 4. Disentangled *I*-band light curves of three short-period double-mode RR Lyr stars marked with a blue circle in Fig. 3.

tional modes are significantly smaller than the amplitudes of the dominant modes. Double-mode RR Lyr stars of the same type were studied by Prudil *et al.* (2017) based on the OCVS. They considered several possibilities (radial modes in unusually high metallicity RR Lyr stars, binary evolution pulsators, non-radial modes) and found no convincing scenarios explaining the nature of the secondary periodicities in these objects. Since Prudil *et al.* (2017) suggested that the primary periods in these objects correspond to the fundamental-mode pulsations, we tentatively classify them as RRab variables, while their secondary periods are given in the remarks in our catalog.

7.1. Group of RRd Stars with $P_{1O}/P_F \approx 0.74$

During the preparation of the OGLE-III catalog of RR Lyr stars in the Galactic bulge (Soszyński *et al.* 2011), we paid attention to a distinct group of 16 double-mode variables that are clumped around $P_F \approx 0.44$ d and $P_{1O}/P_F \approx 0.74$ in the Petersen diagram. Soszyński *et al.* (2014) extended this list to 28 objects and no-

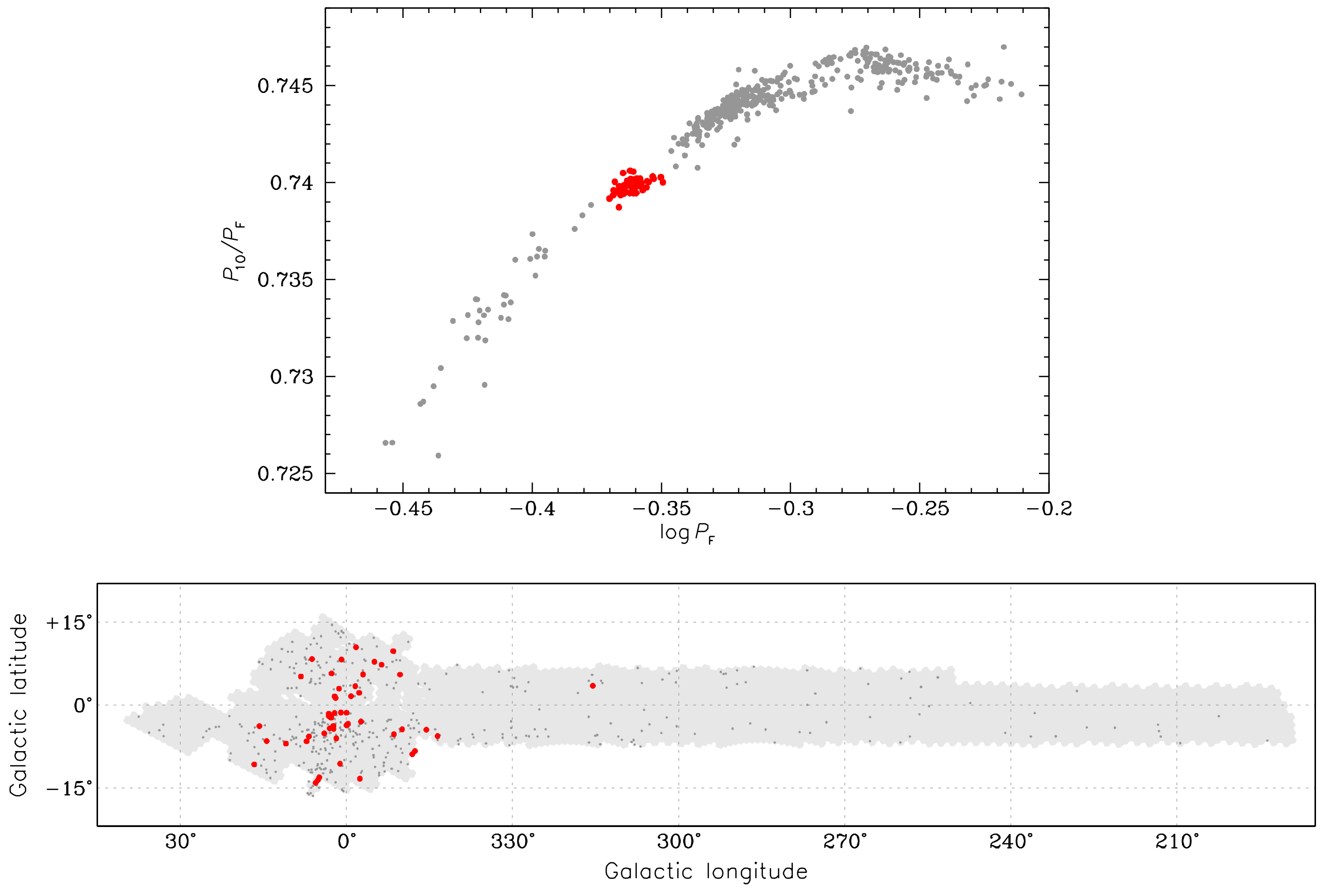

Fig. 5. *Upper panel:* Petersen diagram for "classical" RRd stars. Red points show the compact group of 50 RRd stars with $P_F \approx 0.44$ d and $P_{1O}/P_F \approx 0.74$. *Lower panel:* spatial distribution of the same stars on the sky. The gray area shows the OGLE-IV footprint.

ticed that their spatial distribution is consistent with a stellar stream that nearly vertically crosses the bulge. It suggested that these stars belong to a relic of a disrupted cluster or dwarf galaxy. However, Kunder *et al.* (2019) found that these pulsationally clumped RRd stars have a large range of radial velocities and proper motions, which indicates that they do not belong to a coherently moving group of stars as would be expected for stellar streams.

In the upgraded collection, we increase the number of double-mode RR Lyr variable with $P_{\rm F} \approx 0.44$ d and $P_{\rm 1O}/P_{\rm F} \approx 0.74$ by additional 22 stars. In the Petersen diagram (red circles in the upper panel of Fig. 5), these objects are still clumped in a separate compact group. The sky distribution of all these stars is shown in the lower panel of Fig. 5. All but one of these stars are located in the Galactic bulge and are roughly symmetrically distributed around the Galactic center. Thus, our extended sample of RRd stars confirms the conclusion of Kunder *et al.* (2019) that the stellar stream turned out to be an illusion resulted from a small number statistics and incomplete coverage of the Galactic bulge by the regular OGLE-IV fields.

Nonetheless, these 50 RRd stars with period ratios around 0.74 are clumped in a separate group in the Petersen diagram, which may be a signature of their common origin. It is likely that these stars are indeed relics of a cluster or galaxy accreted by the Milky Way, but any kinematic signature has now been lost. Such a scenario would be in agreement with the hierarchical merging model for Milky Way formation.

8. Conclusions

We carried out a systematic search for RR Lyr stars in the OGLE GVS fields covering Galactic disk and outer bulge. We identified more than 39 000 RR Lyr stars, which doubles the number of Galactic RR Lyr stars included in the OCVS. The explored area of the sky was increased by a factor of 15 compared to the regular OGLE footprint in the Galactic bulge.

About 40% of the newly identified RR Lyr stars have not been included in any existing catalog of pulsating stars, but the greatest advantage of our collection is an exceptionally high level of completeness (94%) and a very low contamination. Our sample is complementary to other large catalogs of RR Lyr stars in the Milky Way halo. The astrophysical potential of the OGLE collection of RR Lyr stars in the Galactic bulge and disk cannot be overstated. It allows one to study three-dimensional structure of the old stellar component in the vicinity of the Galactic plane and in the bulge-halo transition region, to answer the question what fraction of the sample is inherent to the bulge and disk and what fraction is just passing by from the halo population, to explore the abundance patterns in the Milky Way, to investigate globular clusters, and interstellar matter distribution. We are also convinced that OGLE time-series photometry will be useful in a variety of asteroseismological analyses.

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